NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 556

FURTHER STUDIES OF FLAME MOVEMENT AND PRESSURE DEVELOPMENT IN AN ENGINE CYLINDER

By CHARLES F. MARVIN, Jr., ARMISTEAD WHARTON
and CARL H. ROEDER

1936

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s^2 or 32.1740 ft./sec.^{2}

m, Mass $= \frac{W}{g}$

I, Moment of inertia $= mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu.ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $= \frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L = \frac{L}{qS}$

D, Drag, absolute coefficient $C_D = \frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of *c.p.* from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_o, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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By Charles F. Marvin, Jr., Armistead Wharton, and Carl H. Roeder

SUMMARY

The investigation described in this report, was carried out at the National Bureau of Standards at the request and with the financial assistance of the National Advisory Committee for Aeronautics. Stroboscopic apparatus, previously described, for observing flame movement through a large number of small windows distributed over the head of a spark-ignition engine was used in following flame spread with combustion chambers of different shapes at two engine speeds and for a variety of spark-plug locations including single and twin ignition. The principal factors influencing flame movement in the engine are discussed, and the lack of reliable information regarding their separate effects upon the structure of the flame and its speed of propagation are emphasized.

INTRODUCTION

The explosion in a gasoline engine is not an instantaneous but a progressive process, a flame originating at the spark plug and spreading throughout the combustion chamber. The development of pressure and the resulting production of power is dependent upon the nature of this flame spread, as is also the "roughness" of the engine associated with explosion shock and and the "knock" that accompanies detonation. Knowledge of the fundamental facts regarding the actions in the gaseous contents of the engine cylinder during the combustion period is thus important in connection with the design of efficient and smoothly operating engines.

A previous report (reference 1) presented results showing flame movement to all parts of the combustion chamber and simultaneous pressure development in an engine operating on diverse gaseous fuels. The effects of varying the mixture ratio, degree of dilution, charge density, spark advance, and engine speed were measured using a flat cylinder head at compression ratios of 3.6 and 5. The experiments described in the present report give results of a similar nature, obtained by operating the engine on motor benzol with four differently shaped combustion chambers, each giving a compression ratio of 5, and with various arrangements of single and twin ignition. The results of both sets of measurements are reviewed in a general discussion of the major basic factors influencing flame velocities in the engine.

APPARATUS AND PROCEDURE

The 4-stroke-cycle, single-cylinder, L-head engine of 3¾-inch bore and 4-inch stroke, the auxiliary apparatus, and the procedure described in reference 1 were used in the present measurements with only minor changes to facilitate observation and improve precision.

The four special cylinder heads of approximately 5:1 compression ratio with combustion chambers of different shape are shown in figure 1. Head B is the flat steel head used in the experiments of reference 1. Head C, domed over both cylinder and valves, was made from the original cast-iron head of the engine. Heads D and E, domed over the valves alone and with small clearance over the piston, were made of cast brass and differed only with respect to the inward protrusions shown clearly in the photograph of head E. All heads were water-cooled, head B having a separate system not connected with the block.

Each head was provided with a large number of small windows symmetrically distributed over the combustion chamber. These windows were observed through a stroboscope that provided a momentary view at the same point in successive cycles. By varying the timing of the view, it was possible to follow the progress of the flame as it spread from the spark plug to all parts of the charge. Possible positions of the spark gap are shown in the photograph of head B.

Pressure changes during combustion were measured with a balanced-diaphragm indicator of the type described in reference 2.

In order to check the visual observations and to secure a permanent record of the flame travel, photographs like those shown in figure 2 were taken through the stroboscope on many of the runs. The set-up used for this purpose is shown in figure 3. For convenience in analyzing the results, a cardboard mask, showing an outline of the combustion chamber and relative positions of piston and valves, was placed just over the head. Holes punched in the mask permitted a view of the flame through the windows. A small camera loaded with panchromatic motion-picture film was mounted at the stroboscope eyepiece and focused on the head as viewed in a mirror placed above the engine. The stroboscope thus acted as a high-speed shutter giving a very brief exposure once each explosion at the same point in the cycle. When taking a picture, the camera shutter was usually left open for 30 seconds, thus exposing the film to a selected phase of about 250 explosions (at 1,000 r. p. m.). A run included a series of such composite pictures taken at successive 2° intervals during the period of inflammation. Each negative was identified by including in the picture small cards showing run number and stroboscope setting, the latter being expressed in degrees of crank rotation before top dead center (BTDC) or after top dead center (ATDC).

Motor benzol was used as fuel in all runs. Air and fuel flows were adjusted to maintain approximately optimum mixture ratio and a constant weight of charge per cycle equivalent to 75 percent volumetric efficiency for atmospheric conditions of 760 mm of mercury pressure and 20° C.

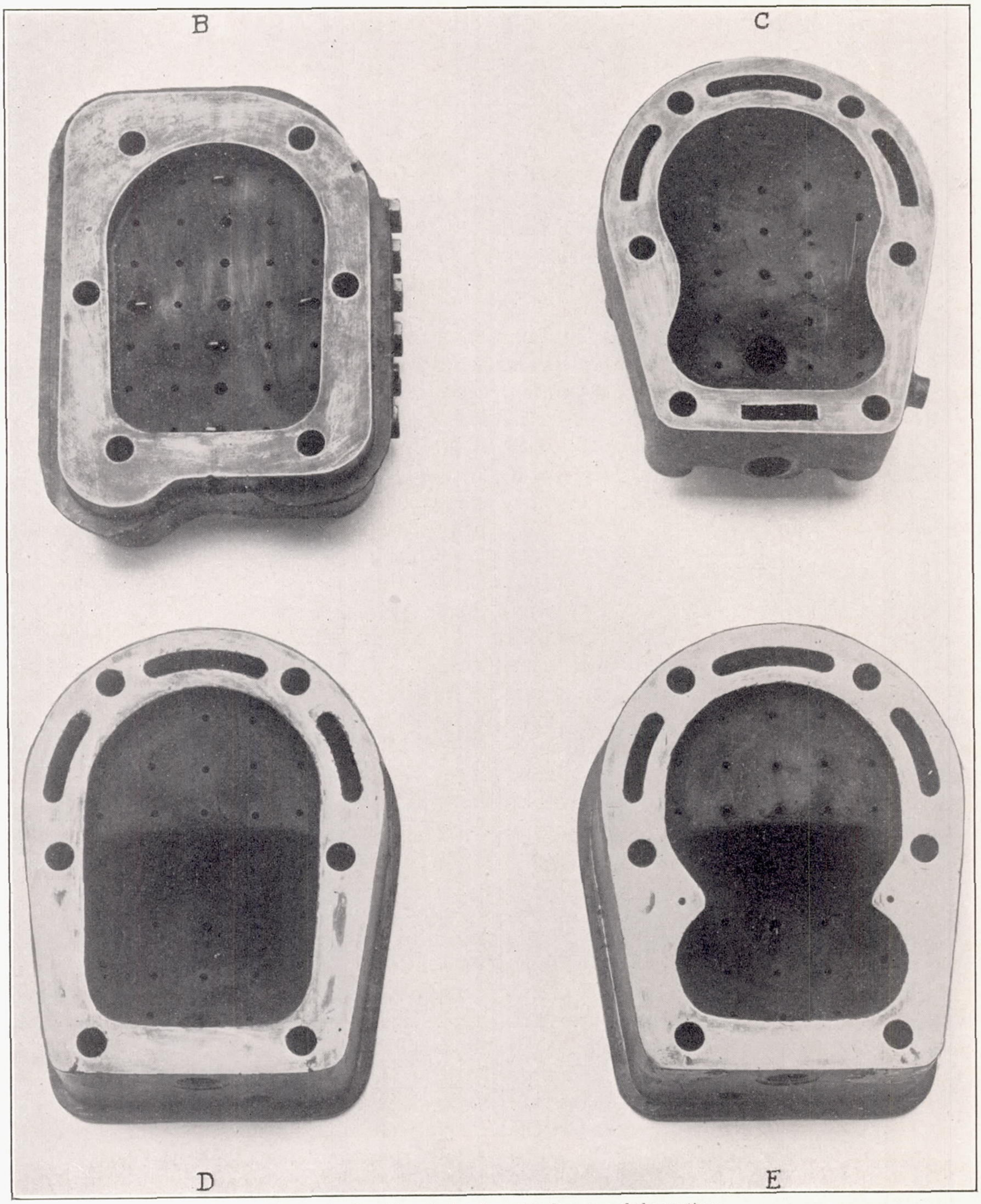


FIGURE 1.—Special engine heads used in flame-travel observations.

RESULTS OF EXPERIMENTS

General characteristics.—During a normal explosion in the engine cylinder, the spark initiates a luminous region that spreads rapidly in all directions from the plug, gaining in brightness as it spreads until the whole charge is inflamed. Although the luminosity decreases as the piston recedes, it is usually visible far down on the expansion stroke.

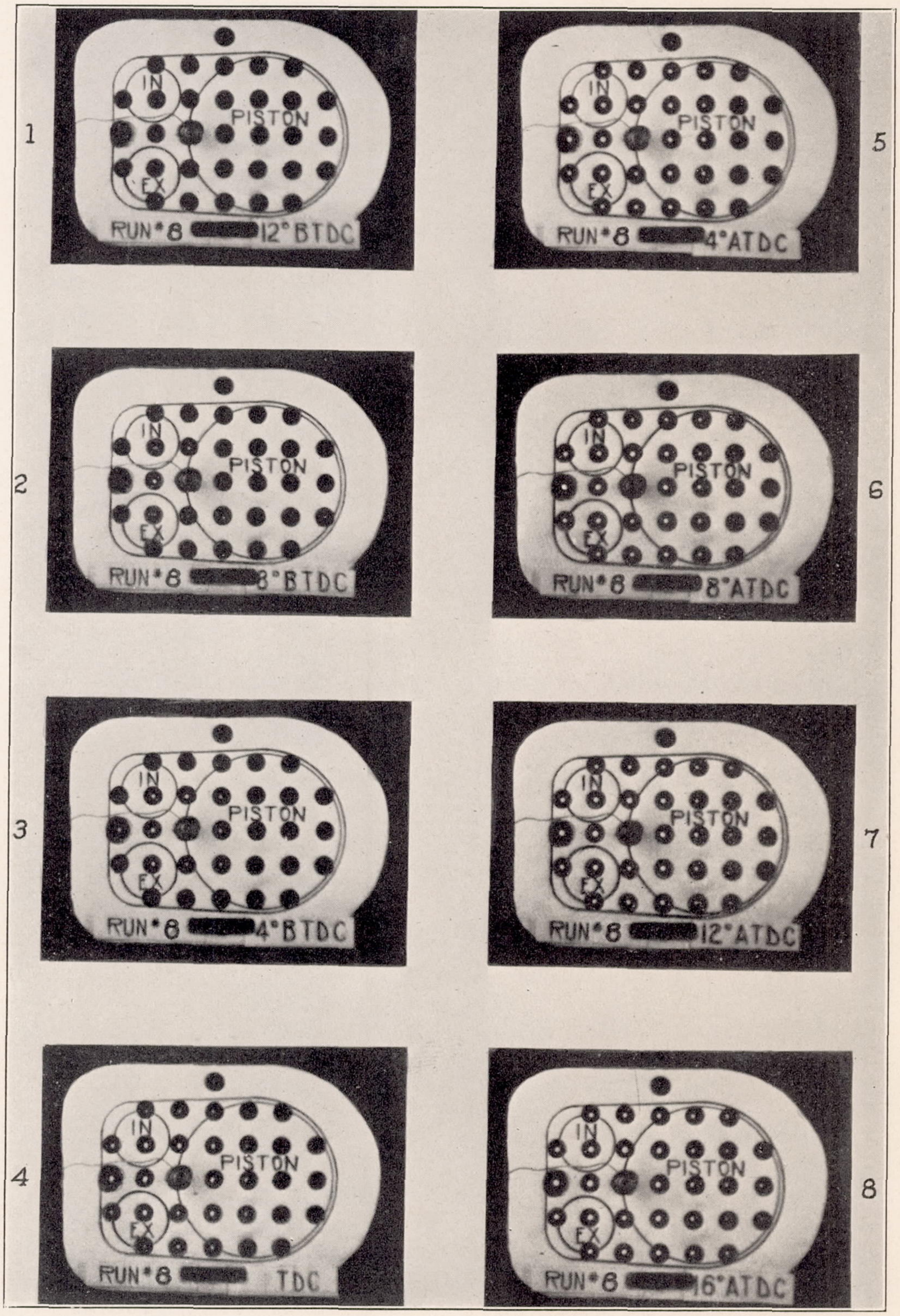


FIGURE 2.—Typical photographs showing spread of flame; 20° spark advance; head B; 1,000 r. p. m.

Successive explosions do not repeat exactly either in speed or general pattern of spread, and the diagrams presented here represent the average of many cycles. Owing to the irregularity from cycle to cycle, windows just reached by the average flame front at a given stroboscope setting receive light from some explosions and not from others and therefore appear dimmer on the photographs than windows previously illuminated. The depth of the flame under these borderline windows is also likely to be small, especially in the region of the plug, owing to the probable curvature of the vertical

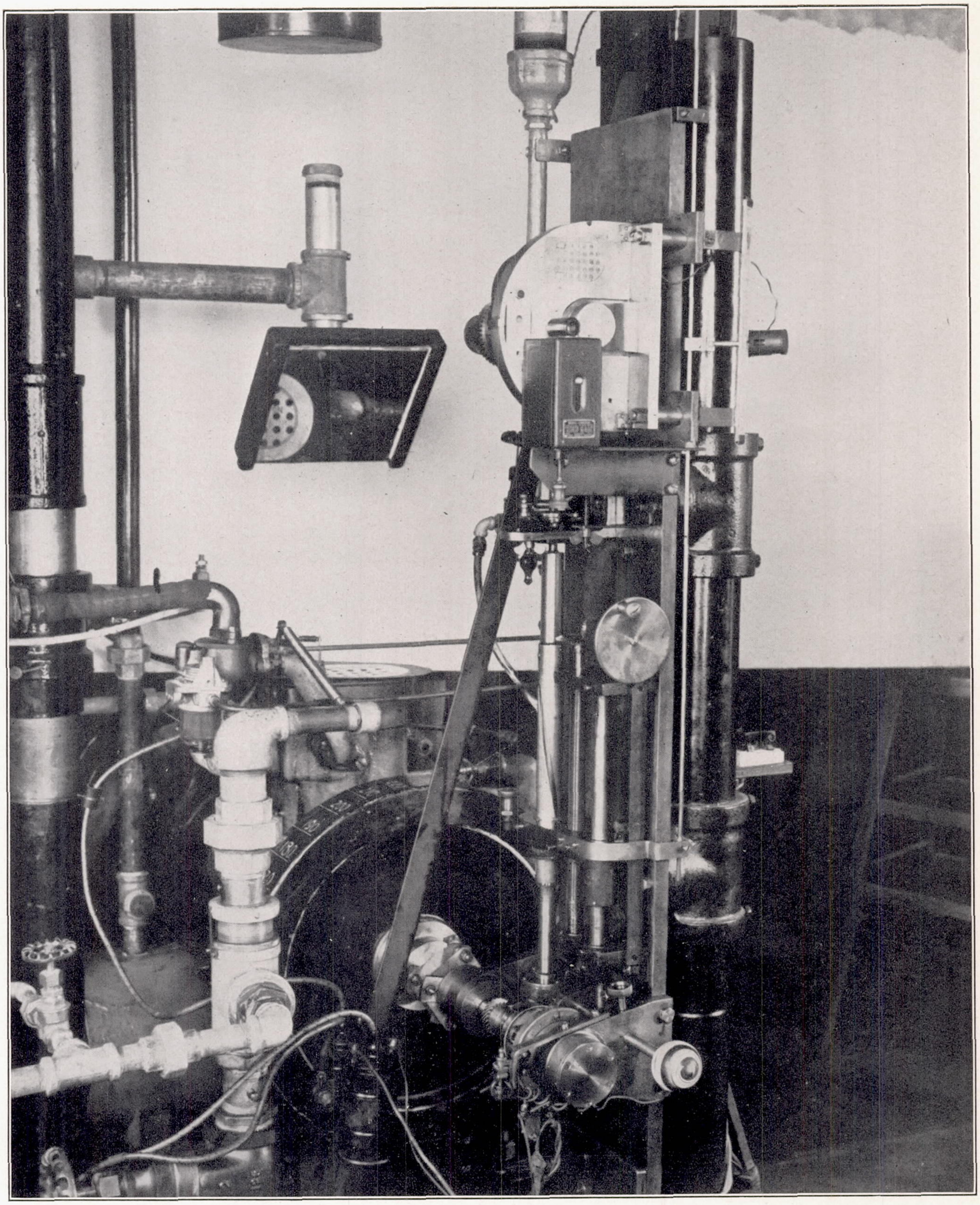


FIGURE 3.—Apparatus used in photographing flame spread.

section of the flame front. In the cases shown by the photographs of figure 2, the depth of the flame over the piston is somewhat less than that at other parts of the combustion chamber, owing to the fact that the piston face rises above the cylinder block. Moreover, this depth is variable to a slight extent due to piston movement. In the other three heads, variable depth results also from curvature of the ceiling of the combustion chamber. Although the windows were thoroughly cleaned before each run, some windows tend to accumulate a deposit of carbon sooner than others, which makes them appear relatively dimmer after a short period of operation. In addition, differences undoubtedly exist in the character and intensity of the illumination emitted at different points within the inflamed gases.

In spite of these time and space variations in the intensity of the illumination, there is usually a sharp distinction between the inflamed region and the adjacent dark gases, and it is generally possible for a number of operators to estimate, with an average uncertainty of about two crankshaft degrees, the time of arrival of the average flame front under a given window, either by visual observation through the stroboscope or by examination of the photographic records. Timing of the spark varied by less than one-quarter of a degree from cycle to cycle.

Effect of combustion-chamber shape.—In figures 4 and 5, flame-front positions at successive 5° intervals after ignition are shown on plan views and vertical center sections of each of the four combustion chambers for two different engine speeds. No observations of flame travel in the vertical plane were made, the flame positions in the vertical sections having been estimated from the plan views. Instantaneous positions of the piston face, where it intercepts the flame fronts, are shown by the dashes. Corresponding sets of indicator diagrams are given in figures 6 and 7. On these and succeeding indicator diagrams the points of complete inflammation, as judged from observations of the flames, are indicated by circles.

The striking feature of these results is their similarity, i. e., pronounced alterations in combustion-chamber shape and engine speed produce only minor changes in flame movement and pressure development as referred to crank or piston travel. Distortion of the flame diagrams from truly concentric spread is not very great in any case. Within a range of 6° (from 11° to 17° after top center) all the flame diagrams reach complete inflammation and all the indicator diagrams arrive at their peak pressures. The maximum rate of pressure rise (about 25 pounds per square inch per degree of crank angle) is approached rather closely in all the diagrams and maximum pressures range between 315 and 365 pounds per square-inch gage.

While differences between diagrams for the different heads are little greater than the experimental uncertainty, some of them are sufficiently consistent to be of interest. Flame travel during the first 15° after the spark is most rapid for the flat head B, slower for the moderately domed head C, and still slower for the higher domes of D and E. The rates of pressure rise during the early stages of combustion show a similar order for the different heads, but the indicator diagram for head C crosses that for head B about 16° after the spark at both engine speeds. Throughout the major portion of the pressure rise, the indicator diagrams for the four heads are nearly parallel and are arranged in the same order at both engine speeds.

The higher maximum pressures attained with head B, together with the fact that compression and expansion lines at both speeds are steeper than for any of the other heads, indicate that the compression ratio for head B was a little higher than for the other heads, probably due to compression of the three gaskets used with this head.

Windows around the piston end of head C became sooted quickly and the very small depth of flame under these windows made readings very uncertain. No reliable readings were obtained in this region at 600 r. p. m.

Effect of engine speed.—As in previous experiments (reference 1), no significant variation in the general pattern of flame spread resulted from a change in engine speed, and the flame and pressure diagrams, plotted with respect to crank position, are nearly the same for 600 and 1,000 r. p. m. Although the differences are slight, they are consistent for all heads and indicate that flame velocity and the time rate of pressure development increase only a little more slowly than engine speed. The increase in the rate of combustion with increase in engine speed is well established and is generally attributed to greater turbulence (references 3 and 4).

Figure 8 is typical of the effect of change in engine speed on the indicator diagrams for all heads. A more gradual slope on the compression and a steeper slope on the expansion lines at 600 r. p. m. is evidence of the greater heat loss from the charge at the lower speed.

Effect of number and location of ignition points.—Special spark plugs that could be inserted at any window location were made to permit a study of the effect of the number and position of the points of ignition. The results with a normal spark advance of 20° are shown in figures 9 and 10. Severe preignition occurred when two of the "hot" special plugs were used simultaneously and, in order to eliminate this feature, a second series of runs (figs. 11 and 12) were made with the spark retarded to 10°. These runs compare single and double ignition under otherwise fixed conditions.

As would be expected, a more rapid pressure rise is accomplished by double ignition although the difference when compared with a single plug favorably placed near the center of the combustion chamber is negligible for the particular conditions of tests.

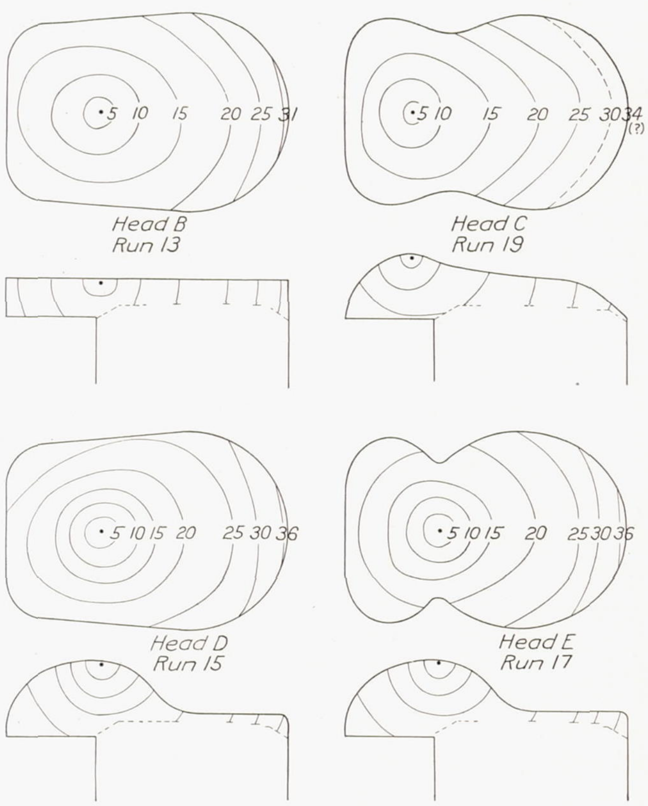


FIGURE 4.—Flame-travel diagrams for different combustion chambers—600 r. p. m.; 20° spark advance.

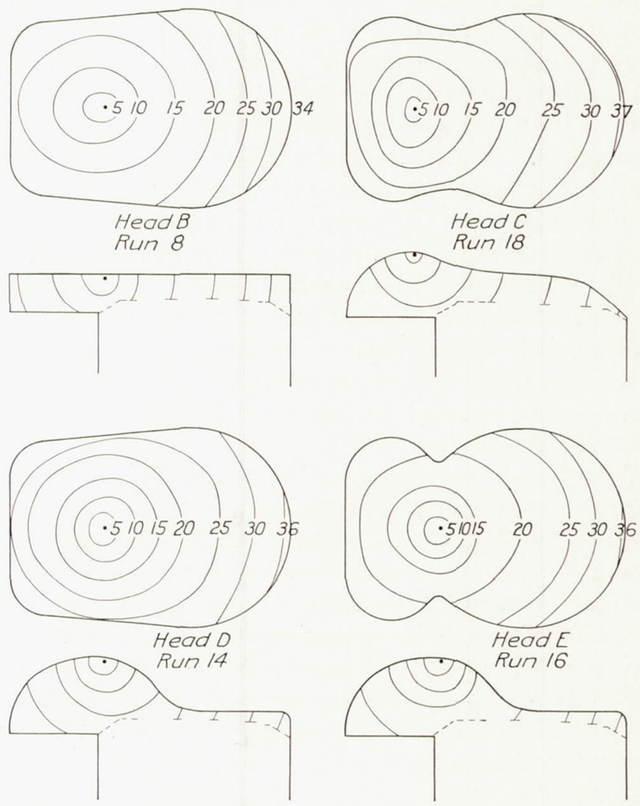


FIGURE 5.—Flame-travel diagrams for different combustion chambers—1,000 r. p. m.; 20° spark advance.

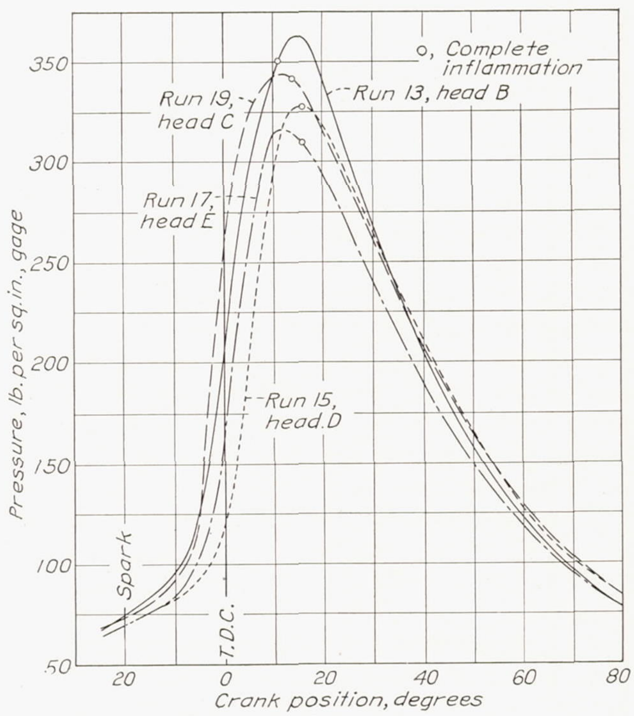


FIGURE 6.—Indicator diagrams for different combustion chambers—600 r. p. m.; 20° spark advance.

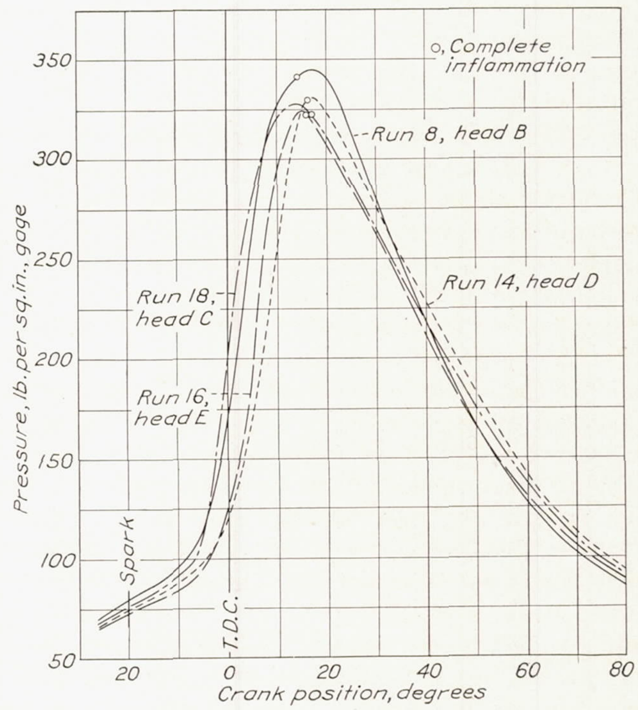


FIGURE 7.—Indicator diagrams for different combustion chambers—1,000 r. p. m.; 20° spark advance.

With single ignition, inflammation time was shortest and pressure rise most rapid when the spark plug was located near the center of the combustion chamber (runs 1 and 8). With side ignition (runs 4, 5, 11, and 12) the distance from the plug to the opposite wall is little greater than for the more central location and inflammation time was about the same except in run 4, which for some unknown reason is not consistent with the other runs of this group. The later pressure rise for the side ignition is probably due to the less rapid increase in area of flame in the early stages as compared with the more central ignition. Locating the single spark plug close to an end of the combustion chamber gave the longest inflammation time and the most gradual and prolonged pressure rise, which was to be expected since the distance the flame must travel is a maximum and the flame area is most restricted.

The marked differences in appearance of the indicator diagrams for the various plug locations and the accompanying differences in power developed would, of course, be greatly reduced if the optimum spark advance for each location had been substituted for the fixed advance used. A comparison of combustion characteristics when the charge is fired at various positions with optimum spark advance for each position is reported in reference 4.

Figure 13 shows the result of changing the spark-gap location from the ceiling of a domed head to a point midway between the ceiling and the block. The change made little difference in the flame spread as viewed from the top, but accomplished an earlier pressure rise because the flame could spread in all directions from the spark.

DISCUSSION

IDEALIZED EXPLOSION

In the review of the many factors that operate more or less independently but simultaneously to influence flame movement in spark-ignition engines, it seems desirable first to recall very briefly the principal features of a highly idealized and simplified explosion. These features are illustrated in figure 14, which shows hypothetical conditions in a long column of gas ignited at one end.

If the tube containing the combustible mixture is open only at the ignition end so that the heated products can escape as they are formed, the flame front will advance into the unburned mixture, and hence along the tube, at a constant speed S_t, which may be called the "transformation velocity" because it is the linear rate at which the charge is transformed chemically.

If the tube is open only at the end opposite the source of ignition, the flame front will still advance into the unburned mixture at this same transformation velocity; but the heated products, now unable to escape to the rear, in expanding push the flame front and the unburned charge forward so that the velocity of the flame front along the tube, although still a constant, is now much greater than in the previous case.

If both ends of the tube are closed, the flame front will start to move at this higher velocity, the long column of unburned gas offering little resistance to the expansion of the first increment of charge to burn. As the flame front advances along the tube, however, the heated combustion products newly formed within it expand in both directions, this expansion being absorbed less and less by the diminishing column of unburned gas ahead and more and more by the increasing column of previously burned charge behind the flame front until, by the time the flame reaches the far end of the tube, all of the expansion is to the rear and the flame velocity in space has decreased to the transformation velocity as a limiting value. This

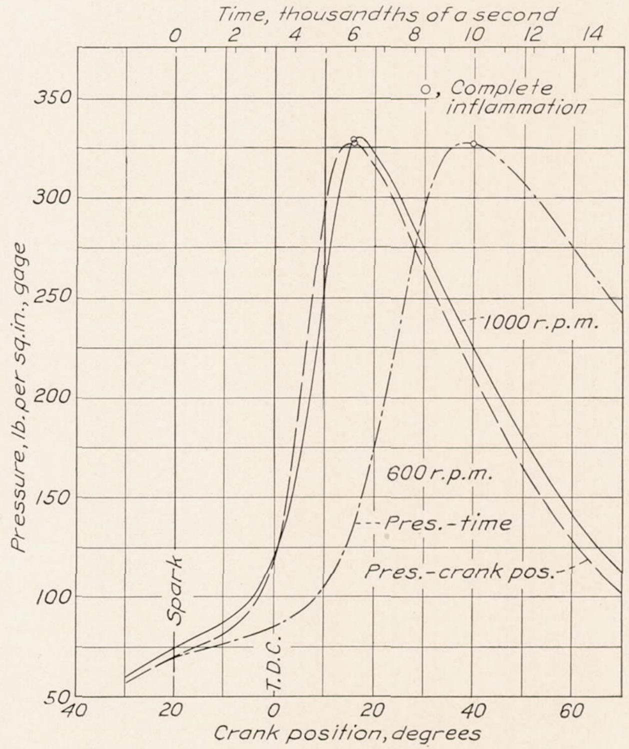


FIGURE 8.—Typical effect of engine speed on indicator diagram.

process has been described very clearly and in considerable detail by Ellis (reference 5).

Thus in normal spark-ignited explosions the velocity S_s of the flame front in space is the sum of the transformation velocity S_t or linear rate at which it advances with respect to the medium supporting it, plus what may be called the "gas velocity" S_u or rate at which the supporting gases are themselves moving through space, or

$$S_s = S_t + S_u \tag{1}$$

The light lines in the diagram show, for the hypothetical case, how elements of charge, originally equally spaced in the tube, move under the influence of the expanding reaction products. Since these lines divide the total mass of charge into equal fractions (tenths) the arrival of the flame front at each successive line completes the burning of another one-tenth of the mass.

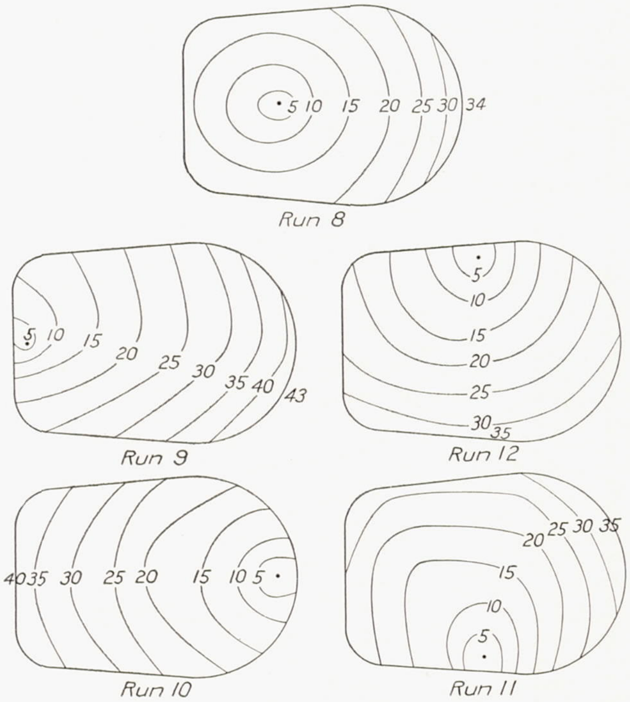


FIGURE 9.—Flame diagrams for different spark-plug locations—20° spark advance; head B; 1,000 r. p. m.

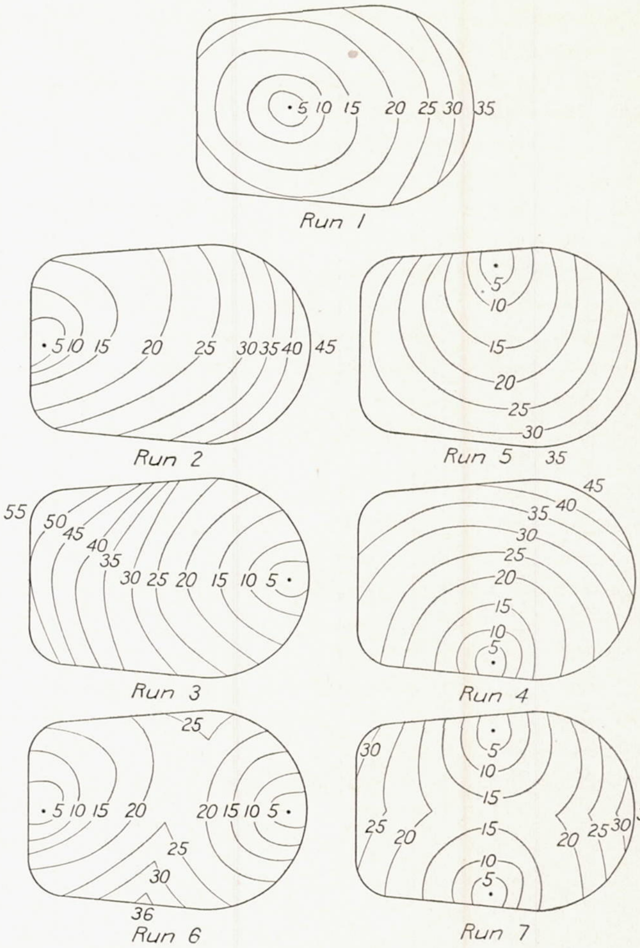


FIGURE 11.—Flame diagrams for different spark-plug locations—10° spark advance; head B; 1,000 r. p. m.

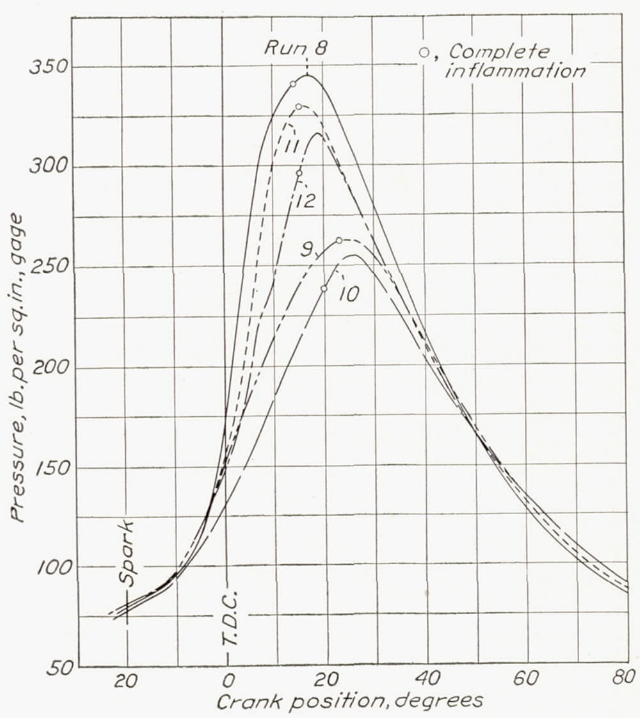


FIGURE 10.—Indicator diagrams for different spark-plug locations—20° spark advance; head B; 1,000 r. p. m.

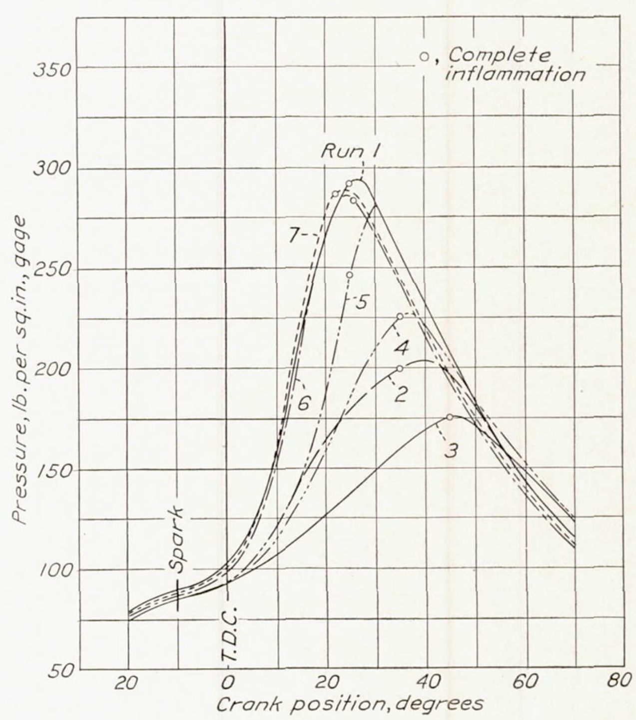


FIGURE 12.—Indicator diagrams for different spark-plug locations—10° spark advance; head B; 1,000 r. p. m.

If pressure rise is assumed proportional to mass burned, a pressure rise against time curve for the explosion may be plotted from the intersections of the flame-travel curve with the light lines.

The mass rate of burning, and hence the rate of pressure rise at any instant will obviously be:

$$M = AS_tD \qquad (2)$$

where A is the area of the flame front and D is the density of the charge undergoing combustion. In the simple hypothetical case, A and S_t are constants so the increasing slope of the pressure curve reflects only the increasing density of the unburned charge. Since for a given explosion this density is determined by the instantaneous pressure, control of the rate of pressure rise must be accomplished through control of A or S_t.

This simple illustration gives a rough first approximation of the gross mechanism of a normal explosion in a spark-ignition engine, and equations (1) and (2) contain the principal factors upon which flame movement and pressure development in the engine depend. The two components of the flame's observed velocity may now be examined separately in greater detail.

FACTORS INFLUENCING TRANSFORMATION VELOCITY

The linear velocity S_t at which a flame front will advance into and transform a nonturbulent mixture of uniform composition and at given pressure and temperature would be expected to be a constant of the mixture. This conclusion is indicated by the fact that the cones of burners operating with constant gas flow are stationary and also by the uniform speed of flame spread in soap-bubble bombs (reference 6). This velocity might be expected to vary with (1) the composition of the unburned charge including both the character of the constituents and their proportions in the mixture, (2) the pressure of the system, (3) the temperature of the unburned charge, and (4) the degree of turbulence in the neighborhood of the flame front. Unfortunately, reliable quantitative information, either theoretical or experimental, as to the separate effects of these four variables upon S_t is either entirely lacking or extremely scarce.

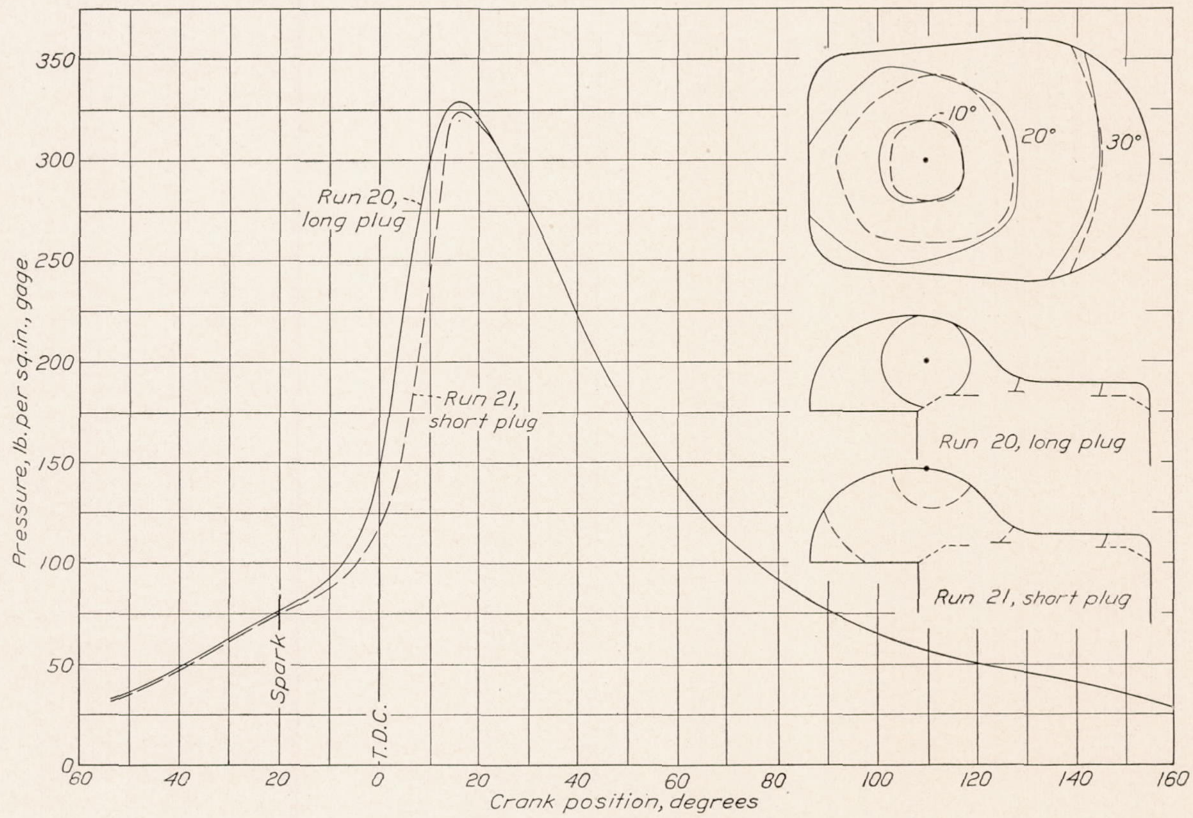


FIGURE 13.—Flame and indicator diagrams for spark plugs with long and short electrodes.

In the engine, all of these factors may vary, generally to an indeterminate extent, from point to point in the combustion chamber and from instant to instant during a single explosion. Also, there is no reliable method of resolving the observed velocity S_s in the engine into its components S_t and S_u. The engine with its highly complicated combustion process is, obviously, not well adapted to the isolation and precise evaluation of the separate effects of fundamental factors, and experiments with the simplest types of gaseous explosions, begun by Professor Stevens, are being continued at the National Bureau of Standards as a means of obtaining this basic information.

Meanwhile, an effort has been made to detect in the engine diagrams any outstanding effects that might be attributed to the four above-mentioned factors, with the realization that it is not possible to explain the observed variations in flame velocity with assurance and that all interpretations must be regarded as speculative to a considerable degree.

Charge composition.—Experiments (reference 1) with equivalent mixtures of different gaseous fuels show rather large differences in observed flame speed S_s. Since the heating values of these mixtures are about the same, little difference would be anticipated in the amount of expansion and, since the same engine-operating conditions were maintained in all runs, a variety of transformation velocities for the different fuels appears to be the only logical explanation for the considerable differences in observed flame speed.

A departure from optimum mixture ratio or an increase in the percentage of residual gases has been found (reference 1) to reduce the observed velocities in

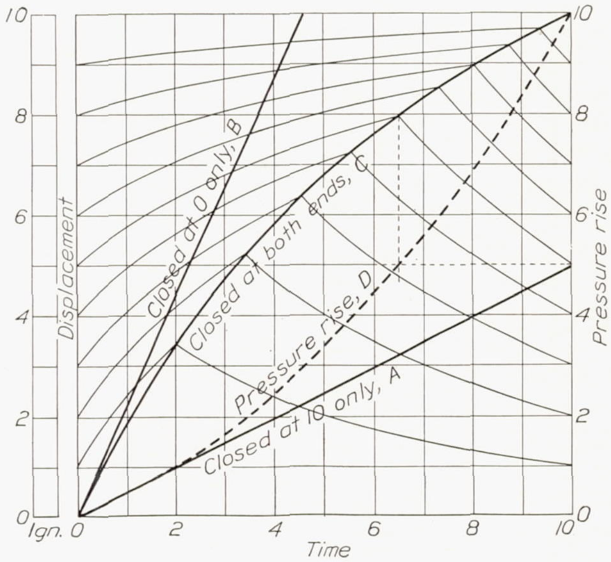


FIGURE 14.—Flame travel and pressure rise for simple idealized explosion in tube.
Curve A. Flame front displacement, tube closed at upper end only.
Curve B. Flame front displacement, tube closed at ignition end only.
Curve C. Flame front displacement, tube closed at both ends.
Curve D. Pressure rise, tube closed at both ends.
Light lines show displacement of planes 1–9, tube closed at both ends.

the engine, undoubtedly through a reduction in both transformation velocity and the amount of expansion in the reaction zone.

Pressure of the unburned charge.—Under conditions where variations in pressure so affect dissociation as to cause pronounced changes in the composition and specific volume of the burned gas, a considerable effect of pressure upon both S_t and S_u might be anticipated. An effect of pressure upon observed flame speed in space, which might be attributed to shifts in equilibrium conditions, has been reported by Fiock and King (reference 7) for moist mixtures of CO and O_2 at initial pressures up to 1 atmosphere. For higher initial pressures in mixtures of hydrocarbons and air, however, these effects are apparently reduced to such an extent that no significant effect of pressure was detected in flame diagrams for the engine or for a constant-volume bomb made from the engine head (reference 1).

Temperature of the unburned charge.—A rise in temperature of the unburned charge may operate to change transformation velocity both directly through an increase in molecular velocities and indirectly, if the rise in temperature is great, by causing preflame reactions that alter composition.

The temperature of the charge at the time the spark occurs may be varied by changes in spark advance, compression ratio, or ratio of fresh to residual charge. Each of these factors was varied in this investigation but any effects of change in charge temperature upon reaction velocity were so confused with the effect of altered combustion-chamber proportions or charge composition as to be indistinguishable.

During the course of an explosion the unburned charge is constantly heated by compression and probably by preflame reactions, and the transformation velocity would be expected to show an accompanying increase. Such an increase would tend to offset the decrease in the gas-velocity component predicted by the idealized explosion and thus minimize variations in the velocity of the flame front in space. A few of the diagrams show a nearly constant velocity throughout the inflammation period. The great majority, however, exhibit low initial velocities, increasing velocities during the early stages and decreasing velocities near the end of the inflammation period. Relatively low velocities at the start and finish are also prominent features of many flame diagrams obtained by other investigators in the absence of detonation. (See references 8, 9, and 10.)

The diminishing velocity as the flame approaches the wall in a normal explosion shows that the increase in transformation velocity resulting from the rise in charge temperature is insufficient to offset entirely the decrease in gas velocity, even in the latter stages of the explosion where the greatest effects of rising temperature might be anticipated. It seems improbable, therefore, that relatively low-charge temperature is entirely responsible for the low-flame speeds during the early stages.

Turbulence.—It is well known that the rate of combustion increases with the degree of turbulence in explosive mixtures and it appears that this increase is brought about by a more rapid advance of the flame front with respect to the unburned mixture; that is, by a higher value of S_t rather than by a distortion of the pattern of flame spread by general swirling gas movements. The most satisfactory explanation for this phenomenon, as well as for the fact that flame speed increases with engine speed, seems to be that small-scale turbulence, in the form of small eddies of a highly random nature, exists throughout the charge in the cylinder and that the degree of this turbulence increases with engine speed.

Kindling of the unburned charge must be accomplished largely, if not entirely, by direct collisions between newly formed materials from the flame and molecules of unburned charge, for the unburned gases can absorb little radiation and the time is not sufficient for conduction and convection to penetrate more than a very small distance ahead of the rapidly advancing flame.

In a perfectly quiescent mixture the process of diffusion alone controls the extent of intermingling of the burned, burning, and unburned phases in the neighborhood of the flame front. In such a mixture the number of collisions contributing to the combustion process per unit area of flame front in unit time is relatively small, and S_t has a minimum value characteristic of the mixture. It is this characteristic value of S_t that is approached or obtained in explosions of quiescent mixtures in bombs and in burner flames.

A vigorous random stirring of the gases in the neighborhood of the flame front, resulting in the mechanical mixture of burned, burning, and unburned materials in a zone of considerable depth would increase the probability of fruitful collisions and raise the value of S_t. Apparently it is through the action of some such local, perhaps even microscopic, turbulence that increased engine speed accomplishes a nearly proportional increase in flame speed.

Less of this type of turbulence in the high domes of combustion chambers D and E may be partly responsible for the slower flame spread and pressure rise in these cylinders as compared with those having the flatter heads. Very little is known about the character and mode of action of this turbulence but, if means can be devised for producing and modifying it locally in the engine cylinder, it should prove to be an effective medium for combustion control.

FACTORS INFLUENCING GAS VELOCITY

In addition to the small-scale random eddies that affect S_t, other more general movements of the charge will influence the observed flame speed S_s without altering S_t. The rate at which the flame front is transported bodily in a direction normal to its surface by such general movements of the gases supporting it has been briefly termed the "gas velocity", S_u. Large-scale gas movements capable of transporting the flame in this manner may be caused by (1) expansion of the burning gases, (2) piston motion during the burning period, or (3) the remnant of the swirl set up during the inlet or compression stroke.

Many published records of individual explosions, particularly in bombs and tubes, show that gas velocity may also be influenced by vibrations and wave effects. These effects are, however, not detected in the average diagrams for as many explosions as obtained by the stroboscopic method.

Expansion due to burning.—It has been seen that for the simple hypothetical explosion in the closed tube (fig. 14), gas velocity is a maximum just after ignition and decreases gradually to zero as the flame reaches the opposite end of the tube. In any so-called constant-volume explosion, each increment of charge overtaken by the advancing flame front is burned, not at constant volume, but more nearly at constant pressure and it therefore expands to an extent dependent largely upon the temperature rise for the reaction. When an increment of charge expands in the reaction zone, it compresess both the unburned charge ahead and the previously burned charge behind, the linear movement in each direction being approximately proportional to the relative volume of gas in that direction. In this process the flame front will be advanced only to the extent that the unburned charge is compressed. If it is assumed that reaction and heat liberation are confined to the flame front, the contribution of expansion to the flame's velocity will be a maximum just after ignition, for at this time the volume of unburned gas ahead of the flame is a maximum in all directions, and the whole expansion is effective in compressing the unburned gas and advancing the flame front. In a nonsymmetrical combustion chamber, the speed at which the flame front is carried away from the point of ignition will begin to slacken first in the direction of the nearest wall, for here the relatively shallow layer of unburned gas has the least freedom of movement normal to the flame with the net result that expansion takes place to the rear, where it contributes to the advance of the flame front in those regions still distant from a wall.

In general, the effect of gas movements set up by the burning of a charge in a nonsymmetrical container is to carry the flame front most rapidly toward the greatest volume of unburned gas; i. e., there is a tendency for the flame surface to shape itself to the container walls. This tendency is very strikingly demonstrated in many of the flame photographs published by Ellis (reference 11). It is detectable also in some of the diagrams reproduced in the present report.

Piston motion.—Both the position of the piston and its rate of motion influence flame velocities in a complicated manner dependent somewhat upon the combustion-chamber shape and spark-plug location.

When the spark occurs, the piston is normally moving upward near the top of the compression stroke. The resulting general compression opposes expansion in the reaction zone and thus tends to reduce gas velocity, the extent of this effect increasing with spark advance. The greater combustion-chamber volumes, however, at greater values of spark advance, favor higher gas velocities. Conflicting influences also control the transformation velocity. With greater spark advance, charge temperature will be lower but local turbulence may be higher for some combustion chambers. That the net effect of these opposing factors upon flame speed in space may be very small, has been shown by the similarity of the flame diagrams (reference 1) obtained with spark advances of 65°, 47°, and 26° in head B.

As the piston moves upward the surge of gas ahead of it tends to blow the newly formed flame away from the piston. This action probably accounts for the first appearance of the flame in the windows on the side of the spark plug remote from the piston, prominent in the photographs of figure 2.

With excessively retarded spark or with slowly burning mixtures, the downward motion of the piston on expansion may noticeably affect flame movement. Figure 11 shows two diagrams (runs 2 and 3) made with the spark plug at opposite ends of the combustion chamber but otherwise under similar conditions. As the spark advance was 10°, the flame front had moved only a short distance from the spark plug when the piston started downward. The rush of gas to occupy the volume vacated by the piston carried the flame front forward when the spark plug was over the valves (run 2) but it blew against the flame when the spark plug was over the piston (run 3) decreasing gas velocity and prolonging the inflammation period about 10°. With a more normal spark advance (20°), inflammation was completed before piston velocity became great enough to produce these effects, as will be seen by a comparison of run 9 and run 10 in figure 9. This effect of piston motion on combustion time, and the influence of spark advance upon it, are also well illustrated in figure 11 of reference 4.

While recession of the piston may either increase or decrease gas velocity, depending upon whether the resultant flow of charge is with or against the advance of the flame front, the total inflammation time is likely to be increased in either case. Thus, if the flame is approaching the piston from above, the layer of gas next to the piston face will always recede faster than the following surge can carry the flame front toward it and transformation velocity will presumably suffer a decrease as the temperature of the expanding charge drops.

General swirl.—The distortion of the diagrams for run 9 of figure 9 and run 2 of figure 11, as though general swirl had carried the flame front forward on one side of the combustion chamber and retarded it on the other, is characteristic of all diagrams obtained with the spark plug in the position shown, although the direction of rotation is frequently reversed. With the spark plug at other locations, the distortion is sometimes noticeable but seldom pronounced. No rational explanation has been found for its erratic behavior, but it would seem that this lack of symmetry could be due only to a general rotary motion of the charge, set up by some unknown cause, or to local regions of high temperature or unfavorable charge composition, which for obscure reasons shift from one side of the combustion chamber to the other.

PRESSURE DEVELOPMENT

The power of an internal-combustion engine is derived solely from pressure developed by combustion of the fuel. Theoretically, power and efficiency are a maximum for instantaneous and complete combustion at top dead center and both increase with increase in compression ratio. Too rapid combustion results, however, in rough operation, whereas increasing the compression ratio tends to cause detonation. The practical problems of combustion control are, therefore, (1) the attainment of the maximum rate of pressure rise consistent with satisfactory smoothness and (2) the suppression of detonation at high compression ratios.

Since flame spread is roughly concentric about a point of ignition, the shortest flame travel and the most rapid pressure rise with a single spark plug will be obtained by placing the gap near the geometrical center of the combustion chamber. A single plug should not be placed so that the flame is traveling away from the piston face as it recedes on the down strike. With slow-burning mixtures or with retarded spark, such a location will cause great additional delay in combustion and pressure development.

Use of more than one plug will further reduce flame travel and increase rate of pressure rise. A detailed study of combustion control by appropriate placing of single and multiple spark plugs, covering a range of speed, spark advance and compression ratio, is reported in reference 4.

CONCLUSIONS

The following conclusions have been drawn from a consideration of the present and previous (reference 1) studies of flame travel and pressure development in a spark-ignition engine.

1. Under all conditions covered, the flame spreads in a roughly concentric pattern about the point or points of ignition.

2. It follows that with single ignition, the shortest combustion time will be obtained by placing the spark plug near the center of the combustion chamber.

3. Still shorter combustion times can be secured by using two or more plugs.

4. Flame velocities are dependent upon the character of the fuel and are reduced by the addition of residual gases to the charge or by departures from the mixture ratio giving maximum power.

5. For normal explosions in engines, flame speeds appear to be independent of pressure and, while they probably increase with temperature, evidence of pronounced effects is lacking.

6. Flame speeds and the rate of pressure development increase nearly as fast as engine speed, which

explains why engines can be operated at very high speeds with only a moderate increase in spark advance.

7. The increase in flame speed with engine speed is believed to be due to an increase in small-scale random turbulence, which affects the structure and depth of the reaction zone and influences the rate at which the flame advances into the unburned charge.

8. For a properly timed explosion of well-prepared charge, there will be very little piston movement during combustion.

9. For excessively retarded spark or slow-burning mixtures, combustion time may be greatly prolonged by downward movement of the piston, especially if the last of the charge to burn is remote from the piston.

10. In general, the spread of flame in the combustion chamber of a spark-ignition engine is controlled by at least six basic factors of major importance that operate more or less independently but simultaneously to determine instantaneous flame velocities in space. Three of these factors—(1) the composition of the unburned charge, (2) the temperature of the unburned charge, and (3) the degree of local turbulence—influence the linear rate at which the reaction advances into and transforms the unburned charge, and are thus of direct importance in determining the rate of pressure rise. The other three—(4) expansion of the gases in the reaction zone, (5) piston movement, and (6) general swirl—affect the rate at which the flame front is carried in a direction normal to its surface by mass movement of the gases comprising it. There is no adequate theory and little or no conclusive experimental evidence now available from which the separate effects of the first three factors upon flame speed can be formulated.

11. It is believed that experiments in bombs conducted under special conditions permitting the accurate evaluation of the speed of the flame front with respect to the active gases (not merely the speed in space) offer the most promising means of securing fundamental information regarding the structure of flame, the mechanism of spread, and the effect of fundamental factors such as charge composition and pressure and temperature in the low temperature range.

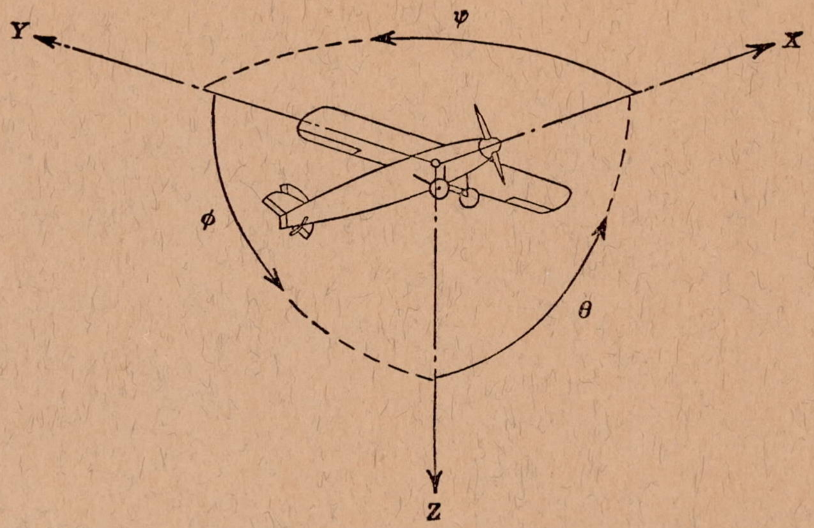
12. In the engine, preflame reactions alter the composition and temperature of the unburned charge to an unknown extent, which probably varies for different fuels. Since these reactions are associated with relatively high temperatures and extremely short heating periods, it would appear that they can be produced and their effects studied with certainty only in an engine or a high-speed compression machine.

National Bureau of Standards,
Washington, D. C., *September 1935.*

REFERENCES

1. Marvin, Charles F., Jr., and Best, Robert D.: Flame Movement and Pressure Development in an Engine Cylinder. T. R. No. 399, N. A. C. A., 1931.
2. Dickinson, H. C., and Newell, F. B.: A High-Speed Engine Pressure Indicator of the Balanced Diaphragm Type. T. R. No. 107, N. A. C. A., 1921.
3. Schnauffer, K.: Combustion Velocity of Benzine-Benzol-Air Mixtures in High-Speed Internal-Combustion Engines. T. M. No. 668, N. A. C. A., 1932.
4. Rabezzana, Hector, and Kalmar, Stephen: Factors Controlling Engine Combustion. Auto. Indus., March 2, 1935, pp. 324–329; March 9, 1935, pp. 354–357; March 16, 1935, pp. 394–397.
5. Ellis, Oliver Coligny de Champfleur: The Rationale of the Movement of Flame through Explosive Mixtures of Gases. Jour. Soc. Chem. Indus., vol. 50, 1931, p. 403.
6. Stevens, F. W.: A Constant Pressure Bomb. T. R. No. 176, N. A. C. A., 1923.
   Stevens, F. W.: The Gaseous Explosive Reaction—The Effect of Inert Gases. T. R. No. 280, N. A. C. A., 1927.
   Stevens, F. W.: The Gaseous Explosive Reaction—A Study of the Kinetics of Composite Fuels. T. R. No. 305, N. A. C. A., 1929.
   Stevens, F. W.: The Gaseous Explosive Reaction at Constant Pressure—The Reaction Order and Reaction Rate. T. R. No. 337, N. A. C. A., 1929.
   Stevens, F. W.: The Gaseous Explosive Reaction—The Effect of Pressure on the Rate of Propagation of the Reaction Zone and upon the Rate of Molecular Transformation. T. R. No. 372, N. A. C. A., 1930.
7. Fiock, Ernest F., and King, H. Kendall: The Effect of Water Vapor on Flame Velocity in Equivalent $CO-O_2$ Mixtures. T. R. No. 531, N. A. C. A., 1935.
8. Glyde, H. S.: Experiments to Determine Velocities of Flame Propagation in a Side-Valve Petrol-Engine. Jour. Inst. Petroleum Technologists, November 1930, p. 756.
9. Schnauffer, Kurt: Engine-Cylinder Flame-Propagation Studied by New Methods. S. A. E. Jour., January 1934, pp. 17–24.
10. Withrow, Lloyd, Lovell, W. G., and Boyd, T. A.: Following Combustion in the Gasoline Engine by Chemical Means. Ind. Eng. Chem., September 1930, p. 945.
11. Ellis, O. C. de C.: Flame Movement in Gaseous Explosive Mixtures. (In 8 parts.) Fuel in Science and Practice, vol. 7, 1928.

U. S. GOVERNMENT PRINTING OFFICE: 1936



Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l = \frac{L}{qbS}$ (rolling) $C_m = \frac{M}{qcS}$ (pitching) $C_n = \frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter
p, Geometric pitch
p/D, Pitch ratio
V', Inflow velocity
V_s, Slipstream velocity
T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$
C_s, Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.
1 metric horsepower = 1.0132 hp.
1 m.p.h. = 0.4470 m.p.s.
1 m.p.s. = 2.2369 m.p.h

1 lb. = 0.4536 kg.
1 kg = 2.2046 lb.
1 mi. = 1,609.35 m = 5,280 ft.
1 m = 3.2808 ft.